

**Water Cycle Dynamics in a Changing Environment
Advancing Hydrologic Science through Synthesis
NSF# EAR 06-36043, Annual Report
For Project Period June 1, 2008 – May 31, 2009**

1. Introduction

Under grant # EAR 06-36043, the Water Cycle Dynamics in a Changing Environment “hydrologic synthesis” project is nearing completion of the second year of work. Building on substantial detailed planning in the first year, the synthesis project team has focused on more targeted, outcomes-oriented activities to advance hydrologic predictability and synthesis science.

Goals

Within our stated goals of advancing predictability in hydrology and advancing synthesis science, we have clearly outlined four principle expectations for Year 2.

- Advance activities that commenced in Year 1 with emphasis on completion of planned or prepared publications.
- Integrate and refocus activities towards main project goals with aim to involve models and real data.
- Build upon Year 1 experiences in synthesis science to promote effective strategies and tools for collaboration.
- Leverage experiences of CUNY group to organize an intensive summer research institute.

Activities

The project has transitioned from defining what synthesis should look like to implementing and testing that vision.

- Focused on two central themes: 1) Interactions between hydrosphere and biosphere processes and 2) Interactions of watershed scale coupled hydrological and biogeochemical processes in intensively managed landscapes.
- Combined bottom-up and top-down approaches to advance fundamental understanding water-ecosystem relationships and network behavior.
- Held a large group planning meeting in October and several smaller informal discussions throughout the year.
- Invested significant time and resources in planning for an intensive summer institute, to be hosted by the University of British Columbia.
- Continued collaboration with CUNY hydrologic synthesis team to further the vision for hydrologic synthesis.
- Assembled a small workgroup to set the agenda for changing water cycle dynamics research.

Outcomes

A majority of outcomes of the second year were initiated in Year 1 though several new activities had early successes.

- Biosphere 2 experimental hillslope facility completes design phase; EOS paper published and 3 journal papers in preparation.
- Special issue of *JGR-Earth Surface* to feature 15 papers on stochastic transport and dynamic scaling.
- Funded proposal linking hydrology and geomorphology in river corridors.
- Submitted proposal examining relationships between soil properties, hydrology and ecosystems.
- Prepared vision paper for the future of hydrology as a holistic systems science.
- Paper on climate and vegetation water-use efficiency at catchment scales is accepted for publication in *Hydrologic Processes*.

Planned Targets

The third year of the project will focus on completing or expanding activities already initiated as well as exploring new research questions within our stated theme areas.

- Host 6 week summer institute for graduate students June-August 2009 with 2.5 day capstone symposium for early career scientists.
- Complete multiple papers based on Year 2 activities and explore opportunities for new activities and proposals as an outgrowth of transformative discoveries.
- Host several small meetings including a planning workshop for core team members and the second STRESS workshop.
- Investigate co-hosting the next summer institute with CUNY team as well as a Chapman conference on synthesis.
- Illustrate the effect of synthesis activities using social network diagrams.
- Initiate further discussions with informal agenda-setting workgroup with aim to recommend a research agenda for hydrology.

This report will be organized around the two project goals – 1) advancing predictability in hydrology and 2) advancing synthesis science. For each goal, two principal expectations and their associated accomplishments are stated. Finally, our expectations for the third project year are listed.

Sections are as follows:

1. Introduction
2. Advancing Predictability in Hydrology
3. Advancing Synthesis Science
4. Third Year Expectations
5. Appendices

2. Advancing Predictability in Hydrology

2.1. Expectation: Advance activities that commenced in Year 1 with emphasis on completion of planned or prepared publications.

Biosphere 2 experimental hillslope facility completes design phase

The April 7, 2009 edition of EOS highlighted the collaborative efforts between this project, CUAHSI and Biosphere 2 EarthScience at the University of Arizona:

Huxman, T., P. Troch, J. Chorover, D. D. Breshears, S. Saleska, J. Pelletier, X. Zeng, and J. Espeleta (2009), The hills are alive: Earth science in a controlled environment, *Eos Trans. AGU*, 90(14), 120.

In “The Hills are Alive: Interdisciplinary Earth Science at Biosphere 2” Dr. Travis Huxman, a synthesis team member and director of B2 Earth Science, describes how the University of Arizona is shaping the research direction of the magnificent research laboratory.

Their goal is for Biosphere 2 to serve as a central for research, teaching, outreach and lifelong learning within the context of global change and water cycle dynamics, especially in semi-arid southwest. The brief paper describes the conversion of the former agricultural biome to the experimental hillslope facility that was designed during three synthesis co-sponsored meetings in 2007 and 2008. These meetings were one of the major foci of the first year, kicking off this significant long term research endeavor. On March 27, 2009, CUAHSI sponsored a cyberseminar in which Dr. Peter Troch, a synthesis team member, presented an overview of this work.

Three papers (titles and authors listed in Appendix A) explaining the critical role of this effort in better understanding partitioning of water and energy at landscape scales are in preparation. The project co-sponsored a 3 day writing workshop at Biosphere 2 in February 2009 to move these papers towards completion. The papers feature major design considerations as well as significant modeling efforts that guided the design and form a predictive basis for hillslope evolution.

Special issue of JGR-Earth Surface to feature stochastic transport and dynamic scaling

With NCED (National Center for Earth-surface Dynamics -- an NSF Science and Technology Center at the University of Minnesota funded under agreement EAR-0120914), our project co-sponsored the STRESS working group meeting in Lake Tahoe, November 2007. This working group seeks to explore ideas, in research and applications, in the area of stochastic transport and emergent scaling in earth-surface processes (STRESS). This meeting and the subsequent collaborative work it fostered generated 15 papers for a special issue of JGR-Earth Surface currently in press. Titles and authors are listed in Appendix B.

Proposal linking hydrology and geomorphology in river corridors is funded

A collaborative proposal stemming from a meeting held in the first year at Northwestern University was funded. In “Collaborative research: Linking scales of geomorphology and solute transport in river corridors” co-PIs and synthesis team members Dr. Aaron

Packman, Dr. Doug Jerolmack, and Dr. Jud Harvey seek to predict the interactions of hydrologic dynamics, geomorphic dynamics, and solute transport in order to improve assessment of long-term average biogeochemical processing rates in river systems. The team will synthesize numerous recent observations and hypotheses developed separately in hydrology and geomorphology in order to ascertain how the linkage between flow dynamics and morphodynamics in rivers controls solute transport over various spatial and temporal scales. By developing new theory that takes advantage of commonality in geomorphic and hydrologic scaling relationships, they will enable explicit evaluation of the integrated process that control solute transport dynamics over a variety of spatial and temporal scales in river corridors.

Proposal examining relationships between soil properties, hydrology and ecosystems is submitted

In January, Professors Siva Sivapalan, Praveen Kumar, Peter Troch and Kathleen Lohse, along with Suresh Rao and Enrique Vivoni (all synthesis team members) submitted a proposal that aims to understand the role of biologic alterations of soil hydrologic properties on soil moisture fluxes and the feedback with the associated vegetation dynamics in water limited ecosystems.

The objective of the proposed three year study is to test the overarching hypothesis that alteration of the soil environment by inputs of soil organic matter and development of macropores increases the access of plants to water and nutrients and thus reduces the need for plants to expend carbon to access those resources. The study will critically examine this hypothesis using a holistic ecohydrologic modeling framework and test model predictions of soil properties with observed field measurements in New Mexico and Arizona.

The intellectual merit of the proposed work lies in highlighting the role of soil heterogeneity in overall ecosystem functioning, including the underlying organizing principles. Ecohydrologic principles will be used to go beyond exploring the adaptation of vegetation to the hydrologic constraints imposed on them, to understanding the constraints that they adapt to, in this case the soil environment. The research will contribute to possible development of a new generation of hydrological models that can capture the net effects of soil heterogeneity without the need for an explicit mapping of that heterogeneity. Models incorporating this evolutionary perspective are critically needed for future hydrologic predictions in the context of accelerating climate and land-use changes, particularly in the Sky Islands region.

We are expecting a positive outcome to this proposal in the next two weeks.

2.2. Expectation: Integrate and refocus activities towards main project goals with aim to involve models and real data.

In the first year, this project focused on defining the scope of efforts and building a team to carry that vision forward. In the second year, we designed to integrate and refocus our activities towards the main project goals with an aim to involve models and real data.

In Year 1, the team selected five major themes to form our umbrella for hydrologic synthesis:

1. Hydromorphology
2. Interactions between hydrosphere and biosphere processes
3. Interactions of landscape processes within intensively managed landscapes
4. Evolution, structure and function of hydrologic subsystems in hillslopes
5. Stochastic transport

These themes branch across scales and sub-disciplines within the earth sciences and truly capture the breadth of understanding hydrologists require to address future problems. However, it became very clear that a narrowed focus (within each year) on specific questions would best facilitate reaching project goals. Though extensive discussions occurred in the first year across all themes, Themes 4 and 5 took center stage. In the second year activities in these areas evolved into writing and background planning.

A planning meeting for Year 2 was held October 6-8, 2008 at the National Center for Atmospheric Research in Boulder, Colorado. This meeting brought together key players from Year 1 as well as new faces to determine how to implement the recommendations of our advisory committee and NSF. Presentations on Year 1 activities and progress were made. Charged with focusing on specific projects, the group broke into four teams to propose next steps. Two of those activities were most promising of transformative outcomes and thus selected to form the focal point for synthesis in Year 2. At this meeting it was also determined that a summer synthesis institute would be an ideal vehicle for conducting this research. Additional details are provided in Section 3.

In this second year, our activities were narrowed down to two important themes: 1) Interactions between hydrosphere and biosphere processes and 2) Interactions of landscape processes within intensively managed landscapes. All activities in Year 2 focused on these, towards culmination in a Summer Synthesis Institute to be held in Vancouver during June 22-August 3.

Interactions between hydrosphere and biosphere processes

To advance fundamental understanding of the water-ecosystem relationship at varying temporal and geographic scales, we've combined bottom-up and top-down approaches.

This hydrologic synthesis activity centers around the empirical observation that, at the catchment scale, the vegetation water use efficiency ($0 < VWUE < 1$) is more or less constant (standard deviation $\leq 5\%$), independent of the climate variability. The VWUE for the growing season is defined as the ratio between actual evapotranspiration and plant water availability. Horton (1933) observed that this ratio is constant (0.78 with std 0.05) for the West branch of the Delaware River at Hancock and Hale Eddy, NY, for the years

1905-1929 (25 years of data). He estimated the VWUE for the growing season (May to October) as the ratio between precipitation (P) minus total discharge (Q) and precipitation minus direct runoff (R) – Figure 1.

Motivated by these early results a team led by Peter Troch and Paul Brooks have taken a two-pronged approach to carry out empirical analyses of (1) annual water balance data for over 100 catchments around the country, and (2) remotely sensed vegetation cover data as measured by NDVI. The objective is to quantify inter-annual variability of water balance, and of vegetation cover, and to discover the connections between these. In parallel, a group led by Ben Ruddell of Arizona State University and Siva Sivapalan, and assisted by graduate student Ciaran Harman, have been approaching the same questions through the use of a multiple wetting front model. These two approaches will then be brought together at the summer synthesis institute in Vancouver, to test fundamental hypotheses that we have formulated through our experience following these two approaches.

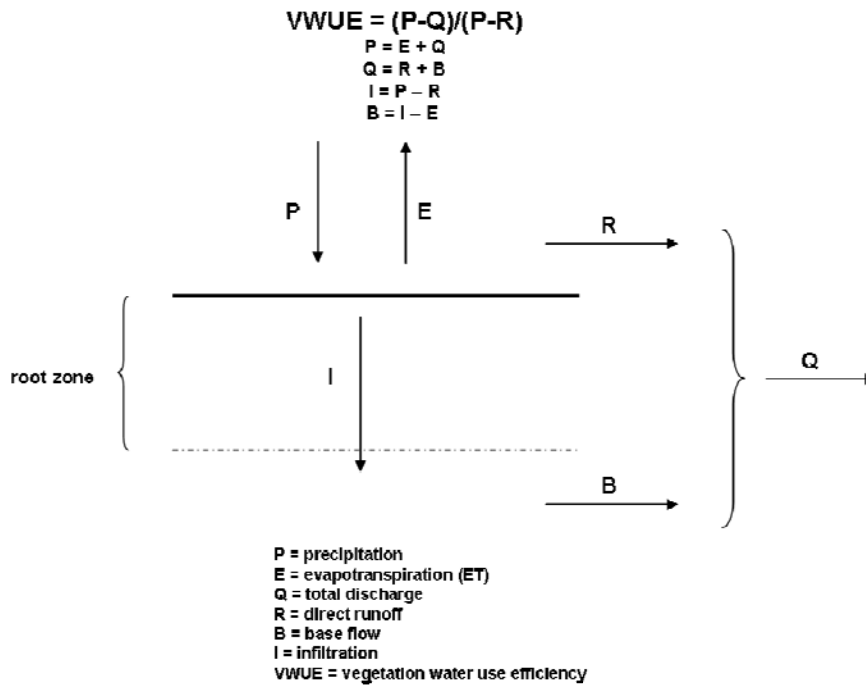


Figure 1

To estimate direct runoff Troch et al. performed a baseflow separation using the concept of a master recession curve (Horton, 1933). Further data analysis using daily precipitation, streamflow, and potential evapotranspiration data from > 100 catchments from the MOPEX database confirms the constancy of this ratio (Figure 2).

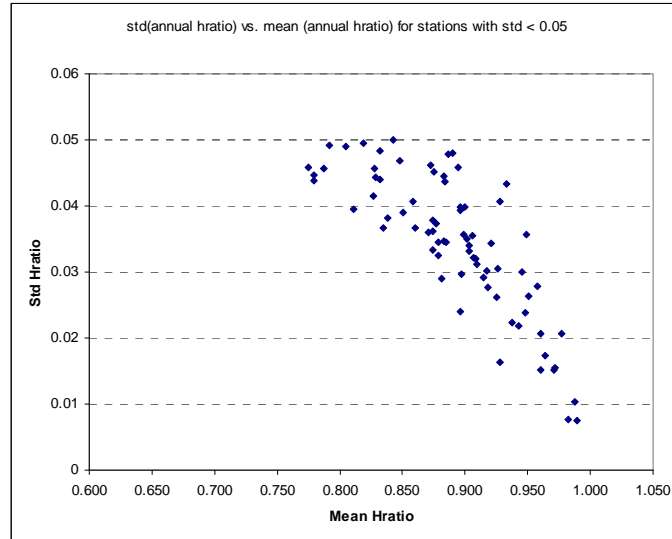


Figure 2: Standard deviation of the VWUE versus mean of VWUE for 101 catchments in the MOPEX database (Hratio = VWUE) (data analysis: Guillermo Martinez). For the 101 catchments, 76 catchments have $\text{std} < 5\%$, 85 have $\text{std} < 6\%$, and 92 have $\text{std} < 9\%$.

Most catchments in this analysis are located in the Southeast region of the US and were selected because these catchments have no significant snow cover during the boreal winter season, thus not affecting spring runoff. The research question that we can derive from this observation is: “How does the vegetation (biome) in a catchment adapt its root water uptake at seasonal time scales such that the vegetation water use remains a constant fraction of the plant water availability independent of seasonal climate variability in P and T?”

Early results from the empirical water balance analyses have been published in the following article:

Troch, P. A., G. F. Martinez, V. R. N. Pauwels, M. Durcik, M. Sivapalan, C. J. Harman, P. D. Brooks, H. V. Gupta and T. E. Huxman (2009). Climate and vegetation water-use efficiency at catchment scales. *Hydrological Processes* (in press).

Several hypotheses can be formulated that either attempt to explain such catchment scale behavior or speculate about the consequences of such behavior for C and N cycles. This activity provides both an empirical and theoretical link between the water, carbon and nutrient cycles at the catchment scales. Moreover, if we can establish a direct link between the (constant) value of this ratio, the region’s climate and catchment properties, we will have new ways to classify catchments with respect to biome behavior and physical characteristics.

Once we have developed ways to evaluate/predict the (constant) value of this ratio, we will have a better theoretical underpinning for our predictions of hydrologic partitioning of precipitation at the catchment scales, as well as for the export and internal cycling of

carbon and nutrients. If valid, this understanding should offer a set of climatic and vegetation-based assumptions that facilitate prediction of the VWUE for a given catchment. Additionally, the existence of such behavior in watersheds potentially provides an invaluable metric for assessing components of uncoupled and fully-coupled (to an atmospheric model) land surface hydrology models.

As mentioned before, our project has taken a two-pronged approach by using observed and modeled data to examine the relationship between the Horton Index and Leaf Area Index (LAI). During the summer institute, students and faculty will attempt to identify at least one ecosystem strategy or optimality principle which can explain this observed relationship. Several different hypothesized ecosystem strategies and optimality principles will be incorporated (one at a time) into a simple ecohydrology model, and the model will be run for a spectrum of ecosystem types and climate zones. Several MOPEX catchments (<http://mopex.cr.usgs.gov/>) will be used as case studies; all necessary modeling inputs are already available for these catchments, simplifying the modeling process. The criteria of success for the modeling exercise will be that several candidate hypotheses are coupled into a simple ecohydrology model, and that inter-annual patterns for H and LAI are predicted and compared with observed values in several different MOPEX catchments for each hypothesis.

Results for each hypothesis will be compared with the null-hypotheses for this modeling exercise. If the incorporation of a hypothesized ecosystem strategy into the basic model improves the results as compared with Hypothesis Zero, then the hypothesis may have merit. Hypothesis 0.1 claims that the catchment water balance is not determined by vegetation in any fashion, and thus 100% of the balance may be described using a combination of climate, topography, snow cover, soil moisture, and the phasing (in-phase/ out-of-phase) of water and energy availability. Hypothesis 0.2 claims that plants do not play any active or strategic role in modifying the critical zone water balance, and can be modeled as simple resistors through which water flows from the rooting zone and evaporates into the atmosphere, in proportion to the Potential Evapotranspiration. Early modeling results using the multiple wetting front model of Ciaran Harman are presented below.

As we can see in Figure 3, an initial Hypothesis 0.2 model which incorporates plant LAI as a measure of plant ET capacity is more accurate in its prediction of the Horton Index, as compared with a Hypothesis 0.1 model that is simply a function of soil moisture. The remaining question is, then, how can we improve further upon Hypothesis 0.2, by incorporating an adaptive, plant-strategy-driven model of ecosystem growth which can accurately reproduce observed H and LAI?

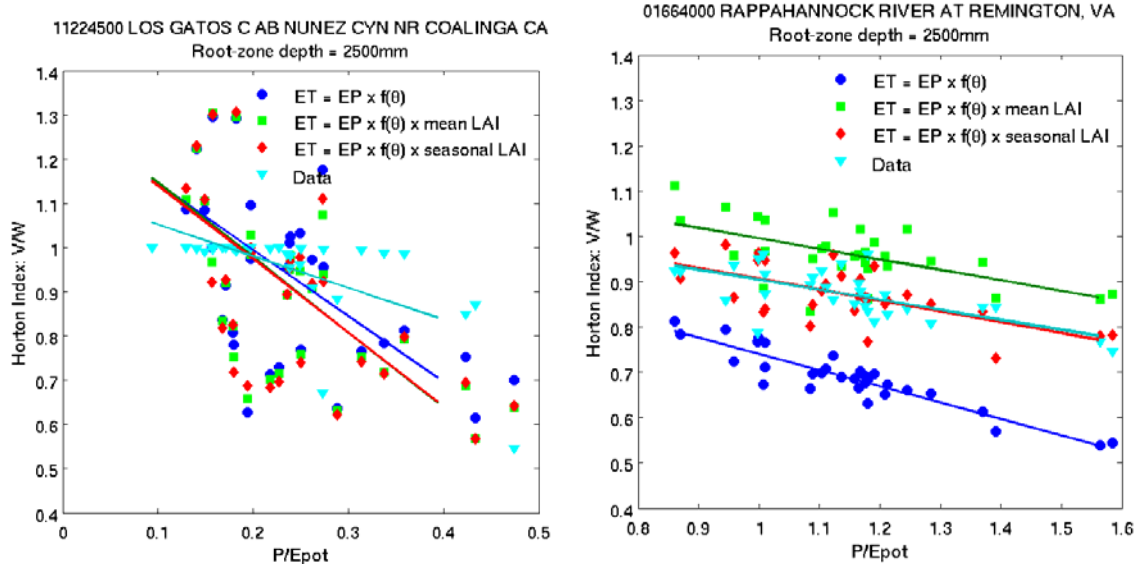


Figure 3: Hypothesis Zero, results for two MOPEX catchments predicting Horton Index using a simple Potential-ET model, (left) for a semi-arid basin in California, (right) for a temperate humid basin in Virginia. Note that the model does well in Virginia (a wet system) and poorly in California (a dry system where energy and water availability are out of phase). Also note that the seasonal-LAI driven model does the best in Virginia, suggesting that the incorporation of a more complex plant-evaporative model improves the quality of predictions. Finally, note that variation of soil depth (results not shown) is a strong control on the Horton Index, such that greater root zone depth results in increased Horton Index. In general, model slopes are steeper (higher sensitivity to annual P) than observed slopes, indicating that the plants have an important role as a filter of precipitation at the catchment scale.

This exercise we will aim to reproduce patterns, rather than seek to achieve a high degree of precision and accuracy in the predictions; if a hypothesized ecosystem strategy can achieve better patterns than Hypothesis Zero, then it is worth pursuing in more depth in future work. Several candidate hypotheses have been proposed (below) regarding adaptive vegetation behavior. The challenge of this work is to determine which of these hypotheses are feasible, to invent an elegant method for adding them to the Hypothesis 0.2 model, and to produce results for the MOPEX catchments.

Preliminary candidate hypotheses:

- Investors vs. opportunists
- H is a special case of a general principle.
- Ecosystems adapt to avoid desiccation.
- Ecosystems adapt to maximize information production.
- Carbon optimality.
- Ecosystems have collective optimality that is different from that of individual plants.

Building on the results obtained in the modeling exercise, during the summer synthesis institute, students and faculty will expand on the number and climatological characteristics of catchments used in the initial work and add remotely-sensed analyses of vegetation structure and activity (LAI, NDVI, ET, PSN, GPP).

Using all 432 MOPEX sites, a subset of 92 sites, FLUXNET sites and additional experimental research catchments, we will ask the following questions:

- How are catchment-based estimates of plant available water related to remotely-sensed information on vegetation across a range of climate and vegetation?
- How does the storage and release of seasonal snow influence the Horton Index and vegetation response?
- Is the magnitude or variability in the Horton Index related to catchment nutrient export?
- experimental research catchments
- Are remotely sensed data on vegetation response biased by climate or species?

This aspect of the project will operate on an overarching hypothesis that variability in vegetation structure and activity will be more closely related to plant available water (estimated using the Horton Index) than to precipitation directly.

In a parallel exercise, and not connected to this year's summer institute, synthesis team members Drs. Paul Brooks, Larry Band, David Gochis and Christine Tague are examining the merging landsurface- and catchment-based approaches for coupling hydrological and biogeochemical cycles through comparison of the RHESSys and CLM models. The objective of this activity is to improve both the conceptual understanding and quantitative model representations of how water, carbon, and nutrient cycles are coupled in four-dimensions (x, y, z, and time).

The general approach is to evaluate the ability of commonly used models, CLM-C/N-Noah from the land-surface community and RHESSys from the catchment community, to represent water and biogeochemical fluxes as well as key state variables (soil moisture, etc.) in the long-term data from experimental/ research watersheds. CLM has strengths in representing vertical (landsurface-atmosphere) fluxes, and RHESSys has strengths in representing lateral (catchment) fluxes. We expect that a direct comparison of the two models will identify specific, testable hypotheses that can be addressed either through subsequent model experiments or data collection.

Depending on the outcomes of the Vancouver summer synthesis institute, the above could be the focus on next year's synthesis activities.

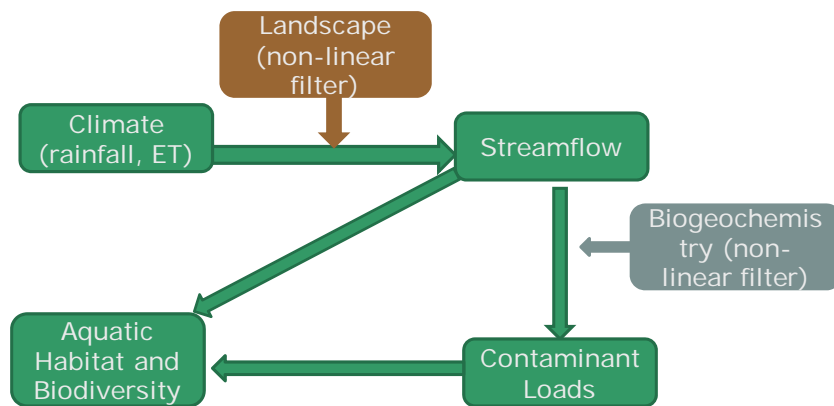
Interactions of watershed scale coupled hydrological and biogeochemical processes in intensively managed landscapes

To address how landscape changes impact hydrology, first understanding scaling dynamics of flow, nutrients and sediments is essential. In this activity, we take a patterns-based, top-down approach to develop a unifying theoretical framework for network behavior.

Current research in watershed hydrology is focused on reproducing the response of individual catchments using detailed process-based distributed models with large number of parameters that are difficult to measure at the scale required. Few studies have recognized the value in studying patterns across catchments with an attempt to classify catchments and identify the dominant drivers of response for each catchment class. Such patterns help in prediction of large-scale responses that are difficult to achieve by “stitching” individual catchment models.

Our overall objective is to create a top-down framework to investigate first order controls on catchment biogeochemical responses to dynamic, human-induced climate and land-use shifts. Specifically we are interested in understanding the filtering and scaling of responses in a converging river network to create signatures/patterns across scales. In order to achieve this we will study contaminant load patterns across (1) climatic gradients, (2) human impact gradients, and (3) spatial and temporal scales, using both data analysis and linked landscape-network models.

Hydrologic systems are complex natural systems consisting of a large number of dynamic components that interact non-linearly to create emergent patterns in space and time. The system can be conceptualized to be comprised of a cascade of “forcings” (or “drivers”) and “filters” (or “attenuators”) that interact nonlinearly to create the modulated spatial and temporal responses or “signatures”. At the top of the cascade is the input rainfall signal, which is attenuated by the landscape that acts as a non-linear filter to create spatial and temporal patterns/signatures in runoff generation and stream flow. Runoff and stream flow, in turn influence the bio-geochemical processes (both on landscape and in the stream network) to create patterns in contaminant loads and concentrations within the stream network. Finally, spatial and temporal patterns in stream flow and contaminant concentrations affect ecosystem structure (e.g., biodiversity) and functions (e.g., services).



Signatures integrate ecosystem structure and function and provide a framework for linkages between disciplines (hydrology, biogeochemistry, ecology) as well as between experimentalists and modelers. Signatures/patterns emerge due to non-linear interactions in space and time of the various components of the hydrologic system. The rate and direction of alteration of these signatures/patterns across human-impact gradients can be used to quantify ecosystem resilience. Some of the signatures that we propose to investigate during the course of the summer institute are as follows:

- Maximum daily concentration (MDC) as function of watershed area (& flow)
- Load as a percent used (LAPU) as a function of watershed area (& flow)
- LAPU as a function of mean annual rainfall or streamflow
- Contaminant load duration curve (similar to flow duration curve)
- pdf of Q plotted as a function of pdf of P
- pdf of mass load plotted as a function of pdf of Q

Of specific interest for this study are nutrient, pesticide and sediment loads. An integrated, comprehensive, but parsimonious, model that uses the concepts of thresholds and dominance from ecological sciences to increase predictive ability is being developed to examine the effects of land use and climate shifts on this suite of signatures. This watershed scale model will follow the representative elementary watershed (REW) framework: processes at scales larger than the REW will be explicitly resolved, whereas processes at smaller scales will be parameterized. A prototype model that couples hydrological (runoff generation and routing in stream network), erosion and sediment transport and biogeochemical cycles (nitrate for a start) has been completed and is undergoing tests at the moment.

To look at nutrients and pesticides, four watersheds of approximate size 400–500 km² will be selected for the purpose of the summer institute. Four scenarios will be selected for each of the watersheds – 1) base case that represents present conditions, 2) temporal shifts in climate, 3) intensification of land use, 4) effect of extreme events. We will study how these drivers propagate through the river network to alter the “base case” signatures across scales. The summer institute activity provides a conceptual and modeling framework for studying the impacts of human-induced land-use and climate shifts on hydrologic and biogeochemical signatures across scales.

To examine signatures in sediment yield with this model, data from several basins are being assimilated, including the Mississippi River, the Yellow River and the Yangtze River. Sediment yield provides a simple lumped representation of the linkages between the erosion processes which operate within the drainage basin and the downstream sediment delivery.

A number of studies have attempted to model and explain regional or global sediment yield trends in terms of climate, topography, and landscape history. However, several problems have arisen, including data quality and the lack of accepted extrapolation procedures and issues of scale dependency.

Thus, in this work we seek to:

- Examine the spatial and temporal variation in sediment yield using the regional sediment yield relations for the landscape.
- Examine the magnitude and frequency of sediment mobilizing events (hydrologic VS Geomorphic Magnitude and frequency, spatial patterns).
- Explore the geomorphic connectivity of the landscape, linking sediment sources (slopes, banks and bed) to sediment yield using reach-scale budgets.
- Explore the response of the landscape to land use and soil conservation practices (has been studied for small basins but not at the landscape scale).
- Identify possible landscape responses to climate change and other disturbances.
- Determine whether it is possible to transfer findings from one scale of investigation to another.

This aspect of the project is important for identifying sources of sediment in river basins, measuring soil erosion, determining rates of landform change and testing land use/management practices.

Summer Synthesis Institute, Vancouver, June 22-August 5

We see the summer institute not just as a culmination of the preparatory work that we have done in Year 2. Under both themes, we have assembled the necessary data, carried out considerable preliminary data analyses, developed the necessary models, and have formulated hypotheses to be tested during the intense activity afforded by the synthesis institute.

We consider the synthesis institute as a fantastic opportunity to generate new ideas and harness the power of intensive, collective thought. We expect students and faculty mentors to leverage these collaborations to not only test hypotheses, but form new conceptual frameworks for addressing the questions at hand. We are currently in the process of preparing the students through a series of cyberseminars, which will provide them with background knowledge, familiarity with the datasets and models, to the degree that they can get into the research once they arrive in Vancouver.

We have also challenged the students and faculty mentors that multiple papers and several new proposals are expected as outcomes from this robust second year of activities. A list of students and faculty mentors is included in Appendix D.

Collaboration with CUNY hydrologic synthesis team

The UIUC synthesis project has participated in ongoing discussions with our sister team at CUNY as well as CUAHSI to establish a joint agenda and mutual goals for synthesis in the near and long term. In addition to this routine communication, project leaders and team members have actively participated in both endeavors and developed new collaborations. Following the October 2009 meeting in Boulder, Suresh Rao and Nandita Basu engaged in exploratory discussions with Mark Green. Mark also made contact with

Rina Schumer, an active synthesis team member. Praveen Kumar participated (February 2009) in a meeting of the Long Term Hydrologic Change: Disturbance Legacies in Material Fluxes Working Group, led by Dan Bain and Mark Green, in which legacy effects were explored within the context of LTER sites and data sets. A concept paper from this workshop is in preparation.

Setting the agenda for changing water cycle dynamics research

As reported last year, Dr. Sivapalan co-hosted a workshop and master class with Dr. Hubert Savenije from the Delft University of Technology in June 2008. The Boussinesq Symposium: *Hydrologic Science for an Ever Changing World: Search for New Hydrologic Concepts, Theories, Models and Practices* brought together leading international experts to articulate their vision for a new hydrology, combining new hydrologic concepts, theories, models and practices. Through key presentations and panel discussions the aim was to move towards a common consensus regarding what the new hydrology may look like, how it should be taught and practiced, and the strategies we should adopt to accelerate the movement towards this new hydrology.

In a parallel effort to our synthesis activities and as an outgrowth of the Delft symposium, Dr. Sivapalan organized a small sub-group of synthesis team members to discuss a vision for the future of hydrologic science. This group included, in addition to Dr. Sivapalan, Dr. Thorsten Wagener, Dr. Peter Troch, Dr. Brian McGlynn, Dr. Hoshin Gupta, Ciaran Harman, Dr. Suresh Rao, Dr. Nandita Basu, and project coordinator Jennifer Wilson. Through weekly phone discussions, the group sought to define barriers and opportunities for transformative hydrologic research and how the requirements to make accurate predictions will evolve in the future in a changing environment. The group collaboratively prepared a commentary outlining the need for a holistic hydrology in order to be relevant in the context of global change. The paper is about to be submitted to *Science*. Follow-up papers recommending a research agenda and an approach to teaching hydrology are in preparation. These discussions, though requiring a relatively small portion of time, have provided substantial foundational principles on which to build our future synthesis activities.

Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. Basu and J. S. Wilson (2009). Hydrologic science: The elephant in the room. In preparation, to be submitted to *Science*.

3. Advancing Synthesis Science

3.1. Expectation: Build upon Year 1 experiences in synthesis science to promote effective strategies and tools for collaboration.

Our focus in Year 2 has been building upon our Year 1 experiences in synthesis science to promote effective strategies and tools for collaboration. The project has transitioned from defining what synthesis should look like to implementing and testing that vision.

While numerous large and small group meetings were very productive for building the project framework in Year 1, we narrowed our activities and targeted efforts to maximize efficiency and effectiveness. We feel this strategy has been fruitful for bringing specificity and energy to our scientific efforts.

In 2008 we engaged two new team members who now play a key role. Drs. Suresh Rao (Purdue University) and Nandita Basu (University of Iowa) brought interest and expertise in catchment-scale network dynamics and nutrient loading. Additionally, Dr. Ben Ruddell, an assistant professor at Arizona State University and recent UIUC graduate, joined the team in February 2009.

To balance the top-heavy team membership, Year 2 began with a concerted effort to seek innovative modes of engaging students, University staff and early career individuals to advance our initiatives. First, it was decided that the interests and desired research direction of this additional desired help must match that of existing team members. This requirement would provide sufficient incentive to participate in project activities with minimal financial compensation. Secondly, the core project team determined that an intensive summer activity would be necessary to produce the desired quantity and quality of transformative outcomes.

Whereas face-to-face meetings can be very productive under certain circumstances, remote interaction and collaboration can be completely sufficient. Utilizing the two together can maximize productivity and cost efficiency. In this year of the project, the team focused on utilizing email, conference calls, web meetings and cyberinfrastructure for the bulk of communication. The priority was placed on substantial individual work and collaborative efforts preceding any in-person meetings. Monthly meetings of the Principal Investigators and the Project Coordinator aided in keeping the planning and budget on track. A list of meetings with synthesis team members is provided in Appendix C.

Our efforts in 2009 have been centered upon leveraging existing efforts, economies-of-scale and overlap of interests as well as maximizing the efficiency in collaboration.

In August 2008, Jennifer Wilson was hired to serve as synthesis project coordinator. Jennifer received a Masters in Soil & Water Science in 2002 from the University of California, Riverside and spent four years working in the drinking water program at USEPA headquarters in Washington, DC. Jennifer oversees all project activities and provides administrative, logistical and technical support to the synthesis team. Jennifer serves as a central point of contact, thus enhancing efficiency of project activities.

In November 2008, we launched a biweekly email newsletter to keep the larger synthesis group informed of project status, meetings and activities. This newsletter has been instrumental in maintaining interest and engagement of the full team. Though a core group of team members is coordinating the research activities, the newsletter allows

interested researchers to keep up to speed and jump in when the opportunity arises. Frequent, transparent communication is a key role for the project coordinator.

Upgrades to the project cybercollaboratory have been a major behind-the-scenes focus for the project management. With a goal to enhance interactivity and engagement, the project coordinator, project PIs and cost-sharing collaborators at NCSA have implemented several new features. While there are still challenges in team responsiveness, team members have reported substantial appreciation for having a central clearinghouse of information.

Through the agenda workgroup (discussed in Section 2), an alternate collaboration strategy has been explored. The free, open-source web application drop.io has been utilized for date-aware, but not hierarchical document sharing. Our site can be viewed at drop.io/waterdynamics/blog.

3.2. Expectation: Leverage experiences of CUNY group to organize an intensive summer research institute.

In the August – October 2008, after the arrival of Jennifer Wilson as project coordinator, the team focused on narrowing the scope of interest and specifically defining the activities for Year 2. A key outcome of October's planning meeting was the decision to pursue a summer institute. The project PIs had suggested that leveraging students, in some way, would be critical for making the desired progress over the life of this project.

At that meeting, Dr. Mark Green shared his experiences planning for and hosting a summer synthesis institute in 2008 for our sister project at City University of New York (formerly University of New Hampshire). Parts of this model seemed very ideal for our project. The project team came to consensus that 6-10 students would be gathered for 4-8 weeks at a location to be determined. The key difference between our institutes, it was decided, would be hand-selection of students and division of the time into different themed sessions.

During the remainder of 2008, the project leaders considered several locations for the summer institute, including New York City, Champaign, Tucson, Reno and Vancouver. Significant logical reasoning and a willing host in Dr. Marwan Hassan at the University of British Columbia led to the selection of Vancouver. Following this critical decision, a begin date of June 22 was selected to accommodate the schedules of team members of a quarter system academic schedule.

As 2009 commenced, preparation on both the logistical and scientific fronts ramped up significantly for a 6 week institute hosting 8 students and 10 rotating faculty mentors. Ms. Wilson took the lead in contacting potential student participants and faculty mentors as well securing accommodations and other necessities for this event. Together, Dr. Sivapalan and Ms. Wilson pushed the self-identified project leaders to formulate plans for the summer work, as described in section 2.2.

In addition to this intensive research activity, our project has partnered with CUAHSI to sponsor a 2.5 day capstone event to engage early career individuals with the students and synthesis team. We hope this workshop will assist in assessing the progress to date and facilitate a solid framework for Year 3 activities.

4. Third Year Expectations

4.1. Advancing Predictability in Hydrology

Similar to our science goals for year 2, the third year of the project will focus on completing or expanding activities already initiated as well as exploring new research questions within our stated theme areas.

At the conclusion of the summer institute, we expect many papers to be at 50-75% complete. As a result, our immediate activities will surround finalizing these manuscripts as well as preparing proposals that are a direct outgrowth of the activities. We plan to foster ongoing relationships with the participating students and their advisors, thus enlarging the reach of synthesis.

Two synthesis-sponsored events are already planned for this fall. Both will provide a foundation from which to launch the next phase of synthesis activities.

First, a planning meeting of core team members will be held to establish and confirm the research direction for the second half of this project. At this meeting, opportunities to expand current work will be explored as well as proposals from team members for new directions will be entertained. The PIs will make decisions on next steps based on the enthusiasm of participants and the resources available. Also, we expect a majority of proposed projects for the third year to include a summer institute component.

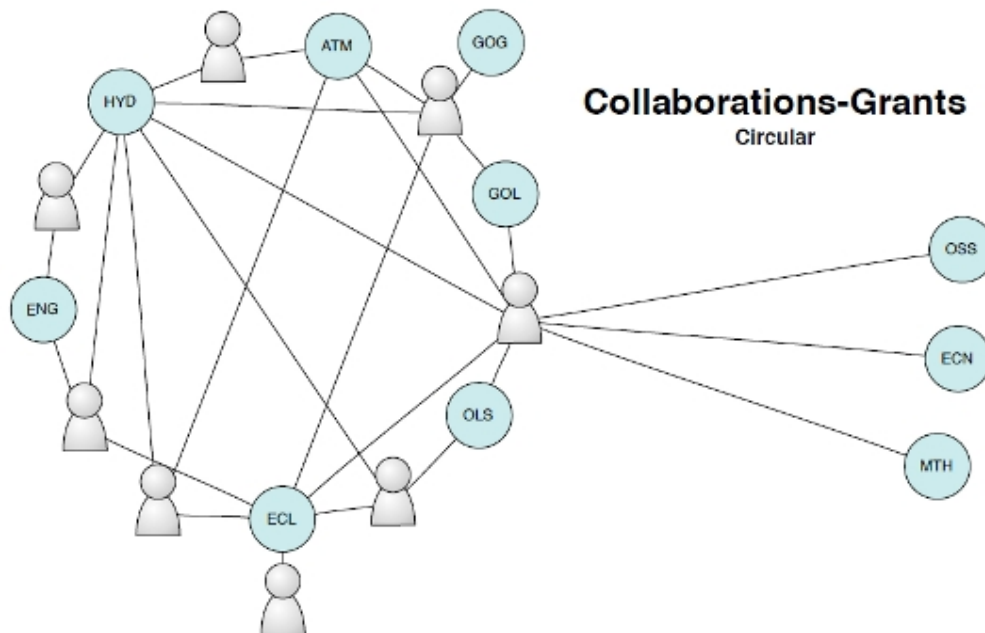
Also this fall, a second workshop on stochastic transport and emergent scaling in earth-surface processes (STRESS) will be held near Lake Tahoe, NV. Following up the success of the first workshop in November 2007, this event will continue to explore geomorphic and hydrologic transport laws to which existing heavy-tailed stochastic theories and fractional calculus tools can be immediately applied as well as outstanding theory required for the development of novel scale-invariant models for Earth surface processes. Much of the catchment-scale nutrient and sediment scaling work is directly applicable to this area of interest due to the strong mathematical underpinnings. Linking these two activities should facilitate exciting connections and new collaborations.

4.2. Advancing Synthesis Science

In the third year of the project, our efforts to advance synthesis science will be tailored to garnering further visibility to project outcomes through targeted outreach and collaborative activities with our synthesis partners and within the community.

This fall, we will begin exploring, jointly with our partners in synthesis at CUNY, the possibility of co-locating our summer institutes in 2010. Hosting these critical events together would leverage not only the project resources, but the combined insights of three years of synthesis science. We will also explore jointly hosting a Chapman Conference on hydrologic synthesis to more formally expose larger segments of our community to the advances made during this project.

Additionally, both opportunities would offer an optimal setting in which to spend extended time in reflection and self-evaluation of these projects. We intend to assume CUAHSI's role as assessor of our project by using our project coordinator, Jennifer Wilson, as the analyst. The survey instrument, intended to explore relationships between individuals and disciplines, will be distributed and results used to construct social network diagrams. As an example of our intended outcome, CUAHSI had prepared this diagram using the baseline results collected in 2007. Furthermore, we will explore collaboration opportunities with other institutions for external assessment opportunities, as deemed relevant and as funds allow.



Finally, the small workgroup that met this spring will reconvene this fall to formalize our discussions on the research agenda for water cycle dynamics in a changing environment. These high-level visioning activities complement the specific, questions-based synthesis activities we have and will undertake. The ideas generated will help shape the direction of hydrologic synthesis.

5. Appendices

A. List of papers in preparation as outcome of Biosphere 2 hillslope design

L. Hopp, C. Harman, S. Desilets, C. Graham, J.J. McDonnell and P.A. Troch
Hillslope hydrology under glass: Design principles and climate testing for the Biosphere2
Hillslope Experiment

K. Dontsova, C. I. Steefel, S. Desilets, A. Thompson and J. Chorover
Coupled modeling of hydrologic and geochemical fluxes to postulate solid phase
evolution in the B2 hillslope experiment

V. Ivanov and D. Jenerette
The Biosphere 2 hillslope experiment: aspects of vegetation-hydrology dynamics in
response to climatic variability (draft title)

B. List of papers in JGR – Earth Surface special issue on STRESS

Ancey, Christophe
Stochastic approximation of the Exner equation under lower-regime conditions

Bradley, D.N., G.E. Tucker, and D.A. Benson
Anomalous Dispersion in a Sand-Bed River

E. Foufoula-Georgiou, V. Ganti, and W.E. Dietrich
A non-local theory for sediment transport on hillslopes

Furbish, D.J. E.M. Childs, P.K. Haff, and M.W. Schmeeckle
Rainsplash of soil grains as a stochastic advection-dispersion process, with implications
for desert plant-soil interactions and land-surface evolution

Furbish, D.J., P.K. Haff, W.E. Dietrich, and A. Heimsath
Statistical description of slope-dependent soil transport and the diffusion-like coefficient

Ganti, V., M.M. Meerschaert, E. Foufoula-Georgiou, E. Viparelli, and G. Parker
Normal and Anomalous Dispersion of Gravel Tracer Particles in Rivers

Harman, C.J., D.M. Reeves, B. Baeumer, and M. Sivapalan
A Subordinated Kinematic Wave Equation for Heavy-Tailed Flow Responses from
Heterogeneous Hillslopes

Hill, K.M., L. DellAngelo, and M.M. Meerschaert
Particle Size Dependence of the Probability Distribution Functions of Travel Distances of
Gravel Particles in Bedload Transport

McElroy, B., and D. Mohrig
The Nature of Deformation of Sandy Bedforms

Schumer, R., and D.J. Jerolmack
Real and apparent changes in sediment deposition rates over time

Schumer, R., M.M. Meerschaert, and B. Baeumer
What are fractional advection-dispersion equations?

Stark, C.P., and F. Guzzetti
Landslide rupture, area and volume distribution, and debris mobilization

Tucker, G.E., and D.N. Bradley
Locality and Non-Locality in Geomorphic Transport Systems: Implications of a Particle-Based Model of Hillslope Evolution

Voller, V.R. and C. Paola
Can anomalous diffusion describe depositional fluvial profiles?

Zaliapin, I., E. Foufoula-Georgiou, and M. Ghil
Transport on river networks: A dynamical approach

C. List of all meetings and purpose: in-person and remote

* indicates student

** indicates young scientist

October 6, 2008

Hydrosphere-Biosphere Interactions Meeting, Boulder, CO

Attendees: Paul Brooks, Dave Gochis, Peter Troch, Nandita Basu**, Darrel Jenerette**, Praveen Kumar, Suresh Rao, Siva Sivapalan, Ciaran Harman*, Jennifer Wilson**

October 7-8, 2008

Synthesis Team Meeting, Boulder, CO

Attendees: Jennifer Wilson**, Kathleen Lohse**, Praveen Kumar, Aaron Packman, Thanos Papanicolaou, Alex Mayer, Mark Green**, Paul Brooks, David Kirschtel, Darren Drewry**, Rina Schumer**, Yong Liu, Ciaran Harman*, Darrel Jenerette**, Roy Rasmussen, Peter Troch, Thorsten Wagener, Siva Sivapalan, Suresh Rao, Nandita Basu**, Dave Gochis, Larry Winter, James Syvitski, Francina Dominguez**

December 5, 2008

Summer Institute Planning, web conference

Attendees: List not available (~10 participants)

December 14, 2008

Informal Synthesis Team Meeting, San Francisco, CA

Attendees: Siva Sivapalan, Don Wuebbles, Rick Hooper, David Kirschtel, Rina Schumer**, Tim Whiteaker**, Anne Lightbody**, Darrel Jenerette**, Alex Mayer, Patricia Saco**, Efi Foufoula, Hal Voepel*, Praveen Kumar, Jennifer Wilson**

Weekly during Winter/Spring 2009

Catchment Network modeling, conference call

Attendees: Siva Sivapalan, Suresh Rao, Nandita Basu**, Sheng Ye*, Jennifer Wilson**

Weekly during Winter/Spring 2009

Horton Index modeling, conference call

Attendees: Siva Sivapalan, Ben Ruddell**, Ciaran Harman*, Bart Rossmann*, Sally Thompson*, Jennifer Wilson**

Weekly during Winter/Spring 2009

Water Cycle Dynamics Agenda, conference call

Attendees: Siva Sivapalan, Thorsten Wagener, Peter Troch, Brian McGlynn, Hoshin Gupta, Ciaran Harman*, Suresh Rao, Nandita Basu**, Jennifer Wilson**

February 11-12, 2009

Catchment Network modeling, meeting in Urbana, IL

Attendees: Siva Sivapalan, Suresh Rao, Nandita Basu**, Jennifer Wilson**, Sheng Ye*, Stefano Zanardo*

February 17-19, 2009

Biosphere 2 Hillslope Design, writing meeting in Oracle, AZ

Attendees: Peter Troch, Jon Chorover, Katerina Dontsova**, Sharon Desilets*, Ciaran Harman*, Luisa Hopp**, Valeriy Ivanov**, Darrel Jenerette**

February 27, 2009

Horton Index modeling, meeting in Urbana, IL

Attendees: Siva Sivapalan, Ben Ruddell**, Ciaran Harman*, Bart Rossmann*, Jennifer Wilson**

March 11, 2009

Summer Institute Overview, web conference

Attendees: Siva Sivapalan, Praveen Kumar, Peter Troch, Paul Brooks, Suresh Rao, Nandita Basu**, Marwan Hassan, Ben Ruddell**, Aaron Packman, Jennifer Wilson**, Sheng Ye*, Hongyi Li*, Ciaran Harman*, Sally Thompson*, Stefano Zanardo*, Antoine Aubeneau*

Bi-Weekly during Spring 2009

Sediment Yield modeling, conference call

Attendees: Siva Sivapalan, Marwan Hassan, Aaron Packman, Antoine Aubeneau*, Hal Voepel*

March 23-26, 2009

Catchment Network modeling, meeting in West Lafayette, IN

Attendees: Siva Sivapalan, Suresh Rao, Nandita Basu**, Stefano Zanardo*, Sheng Ye*

April 7-9, 2009

Horton Index modeling and data analysis, meeting in Tucson, AZ

Attendees: Siva Sivapalan, Ben Ruddell**, Peter Troch, Paul Brooks

May 8 – June 5, 2009

Weekly conference calls to discuss summer institute plans

Attendees: Siva Sivapalan, Ben Ruddell**, Gavan McGrath, Peter Troch, Paul Brooks, Matej Durcik**, Nandita Basu**, Suresh Rao, Aaron Packman, Marwan Hassan, Jennifer Wilson**, Sheng Ye*, Ciaran Harman*, Sally Thompson*, Stefano Zanardo*, Antoine Aubeneau*, Mary Yeager*, Patrick Little*, Hal Voepel*, Bart Rossman*, Andy Neal*

June 21-August 2

Summer Institute, Vancouver, BC

Attendees: Siva Sivapalan, Ben Ruddell**, Gavan McGrath, Peter Troch, Paul Brooks, Matej Durcik**, Nandita Basu**, Suresh Rao, Aaron Packman, Marwan Hassan, Jennifer Wilson**, Sheng Ye*, Ciaran Harman*, Sally Thompson*, Stefano Zanardo*, Antoine Aubeneau*, Mary Yeager*, Patrick Little*, Hal Voepel*, Bart Rossman*, Andy Neal*

August 3-5

Summer Institute Symposium, Vancouver, BC

Attendees: TBD

D. List of Summer Institute Participants and their Affiliation

Administrative Support

Jennifer Wilson – University of Illinois

Sandy Lapsky – University of British Columbia

Faculty Mentors

Murugesu Sivapalan – University of Illinois

Benjamin Ruddell – Arizona State University

Nandita Basu – Purdue University

Suresh Rao – Purdue University

Aaron Packman – Northwestern University

Marwan Hassan – University of British Columbia

Peter Troch – University of Arizona

Paul Brooks – University of Arizona

Matej Durcik – University of Arizona (postdoc)

Student Participants

Antoine Aubeneau – Northwestern University
Ciaran Harman – University of Illinois
Bart Rossman – University of Illinois
Patrick Little – University of British Columbia
Bryan Moravec – University of Arizona
Andy Neal – University of Arizona
Hal Voepel – Desert Research Institute
Sheng Ye – University of Illinois
Mary Yeager – University of Illinois
Stefano Zanardo – University of Padua